

Measurement Induced Entanglement for Excitation Stored in Remote Atomic Ensembles

H.de Riedmatten¹, C.W Chou¹, D. Felinto¹, S.V. Polyakov¹, S.J. van Enk² and H.J. Kimble¹

1. Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, United States

2. Bell Labs, Lucent Technologies, Room 1D-428, 600-700 Mountain Avenue, Murray Hill, New Jersey 07974, USA

hugues@caltech.edu

Abstract: We report the observation of heralded entanglement between remote atomic ensembles. The detection of an emitted photon projects the ensembles into an entangled state with one joint excitation stored in the whole system.

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A critical requirement for diverse applications in Quantum Information Science is the capability to disseminate quantum resources over complex quantum networks. This requires the realization of a quantum memory that would allow the storage and retrieval of quantum states. Atomic ensembles appear to be a promising candidate for this task [1]. In this contribution we report observations of entanglement between two atomic ensembles located on different tables in distinct apparatuses separated by 2.8 meters [2]. Quantum interference in the detection of a photon emitted by one of the samples projects the otherwise independent ensembles into an entangled state with one joint excitation stored remotely in $\sim 10^5$ atoms at each site. After a delay of 1 μ s to demonstrate quantum memory, we confirm entanglement by mapping the state of the atoms to optical fields and by measuring mutual coherences and photon statistics for these fields. We thereby determine a quantitative lower bound for the entanglement of the joint state of the ensembles.

A simple schematic of our experiment is presented in Fig. 1. The protocol starts by illuminating the two ensembles simultaneously with a weak “write” pulse, such that the probability of creating more than one excitation in the symmetric collective mode [1] of each ensemble by spontaneous Raman scattering is very low. (see Fig 1a) Entanglement between the L, R ensembles is created by combining the output Stokes fields 1_L and 1_R on the beam splitter BS_1 , with outputs directed to two detectors D_{1a} and D_{1b} . For small excitation probability and with unit overlap of the fields at BS_1 , a detection event at D_{1a} or D_{1b} arises indistinguishably from either field 1_L or 1_R , so that the ensembles are projected into an entangled state, which in the ideal case can be written as:

$$|\Psi_{L,R}\rangle = \varepsilon_L |1\rangle_L |0\rangle_R \pm \varepsilon_R e^{i\eta_1} |0\rangle_L |1\rangle_R$$

where $|0\rangle_{L,R} = \bigotimes_{i=1}^{N_{L,R}} |g\rangle_i$ is the state with all atoms in the initial ground state, $|1\rangle_{L,R} = \frac{1}{\sqrt{N_{L,R}}} \sum_{i=1}^{N_{L,R}} |g\rangle_1 \dots |s\rangle_i \dots |g\rangle_{N_{L,R}}$ is the state with one collective atomic excitation, and ε_L (ε_R) is the normalized amplitude of photon generation from ensemble L(R). The phase η_1 is determined by the difference of propagation phases from BS_w to the ensembles and from the ensembles to BS_1 , for the write pulses and the fields 1_L and 1_R , respectively. For the verification of the entangled state, η_1 must be constant from trial to trial. In our experiment, it is actively stabilized using an auxiliary

field at 1064 nm.

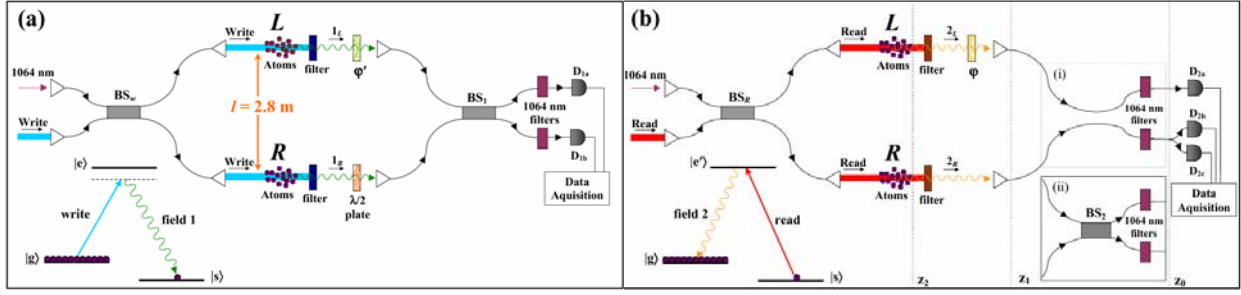


Fig. 1. Schematic of the experiment. (a) entanglement preparation. (b) entanglement detection. We use cesium atoms cooled and trapped in two independent magneto-optical traps at locations L and R.

To verify entanglement, we map the delocalized atomic excitation into a field state (field 2), by applying simultaneously a read pulse to the ensembles (Fig 1b). Since this operation is local, it cannot increase entanglement. The presence of entanglement in the field state is thus a signature of entanglement in the atomic ensembles. The entanglement between the fields 2_L and 2_R is determined by a quantum tomography method, which takes into account various intrinsic and experimental imperfections of the measurement. We consider the following density matrix:

$$\rho_{2_L, 2_R} = \begin{pmatrix} p_{00} & 0 & 0 & 0 \\ 0 & p_{10} & d & 0 \\ 0 & d^* & p_{01} & 0 \\ 0 & 0 & 0 & p_{11} \end{pmatrix}$$

where the p_{ij} are the probabilities to find i photons in mode L and j photons in mode R, and d is the coherence between the $|1_{2L}, 0_{2R}\rangle$ and $|0_{2L}, 1_{2R}\rangle$ states. To measure the diagonal elements, we send the two modes 2_L and 2_R directly to single photon detectors, in order to reconstruct the photon statistics. The coherence term d is measured by combining the two modes at a beam splitter BS₂, and by applying a phase shift to one of the modes. An interference fringe is observed in the conditional counts with a visibility of $\sim 70\%$. A lower bound of the entanglement can be determined by calculating the concurrence C given by $C = \max(2|d| - 2\sqrt{p_{00}p_{11}}, 0) / \tilde{P}$ with $\tilde{P} = p_{00} + p_{10} + p_{01} + p_{11}$. We find: $C_{(1a)} = (2.4 \pm 0.6) \times 10^{-3} > 0$ and $C_{(1b)} = (1.9 \pm 0.6) \times 10^{-3} > 0$ for the states conditioned on a detection at D_{1a} or D_{1b}, respectively. This conclusively demonstrates the presence of entanglement in the fields 2, and hence in the atomic ensembles. The small value for the concurrence seems to be primarily due to the low atoms-light transfer efficiency ($\sim 10\%$). This efficiency can be in principle close to unity.

Our work provides the first example of a stored atomic entanglement that can be transferred to propagating light fields, and significantly extends laboratory capabilities for entanglement generation, with now entangled “qubits” of matter stored with separation several thousand times larger than was previously possible. Although the entanglement creation is probabilistic, the initial detection heralds unambiguously the creation of an entangled state between the two ensembles, which can be stored and is physically available for subsequent utilization.

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